MORPHOLOGICAL CHANGES IN THE NGC 6251 JET

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ABSTRACT

The giant radio galaxy NGC 6251 is a particularly good object for observational tests of relativistic jet models. Due to its high declination and ~0.5 Jy radio nucleus, high quality VLBI images of the central regions of the source can be made with northern hemisphere arrays. In addition, the large-scale radio morphology strongly suggests that the radio axis lies close to the plane of the sky, so Doppler boosting should be less extreme than in the core-dominated superluminal sources. Earlier 18-cm VLBI observations of NGC 6251 revealed an unexpectedly large jet/counterjet brightness ratio and small transverse motion of a feature in the parsec-scale jet, These early results are difficult to reconcile with the simplest symmetric relativistic jet models.

In this paper we present a third-epoch 18-cm VLBI image of the parsec-scale radio jet in NGC 6251, and compare jet morphology over a five year time span. The jet shows a minor brightness peak at nearly the same distance from the core as the "25-mas knot" seen in the first and second epoch VLBI images, This feature is much less pronounced in the third epoch, and a relatively bright, new knot has appeared ~12 mas from the core, If this new component had a constant brightness during the five years separating the first and third observing epochs, then it must have moved away from the core with an apparent speed of at least 1.4 c (compared with an upper limit of 0,23 c for motion of the 25-mas knot). However, we cannot yet rule out a local brightening of the inner jet in favor of a new moving component, We determine

a lower limit for the jet/counterjet brightness ratio of 100:1 within 6 milliarcseconds of the core. We also present a new VLA image of the kpc-scale jet with 3 arcsecond resolution, made from data obtained during the VLBI observations, The rate of decrease in jet surface brightness from pc to kpc scales is similar to jets in known superluminal radio sources.

1. INTRODUCTION

A series of three global M-cm (1.66 GHz) VLBI observations of the giant radio galaxy NGC 6251 have been carried out over a five-year period to test the relativistic twin-jet model for compact radio sources. The large-scale morphology of this source (Waggett and Warner 1977; Willis *et al.* 1982; Perley, Bridle, and Willis 1984; Jones *et al.* 1986) suggests that its radio axis is close to the plane of the sky, and its high declination allows good (u,v) coverage by northern hemisphere VLBI arrays, so it is a good candidate for detection of a pc-scale counterjet (and a poor candidate for highly superluminal motion [Browne 1987; Hough and Readhead 1987]). The detection of a pc-scale counterjet would confirm that the jet formation process is intrinsically two-sided on short time scales.

The first 18-cm VLBI experiment in 1983 (Jones *et al.* 1986) showed a one-sided jet with a weak knot approximately 25 mas from the core (we assume the core corresponds to the strong, unresolved peak at the eastern end of the jet). No counterjet was detected at a limit of 80:1 measured ± 6 mas from the core. For a pair of oppositely-directed jets with bulk velocity β c (in the rest frame of the galaxy), a radio spectral index of -0.5, and oriented at an angle θ from out line of sight, the observed brightness ratio R is given by (Ryle and Longair 1967)

$$R = \left[\frac{1 - \beta cos(\theta)}{1 + \beta cos(\theta)}\right]^{2.5}.$$

If the lack of a detectable pc-scale counterjet is due to a large Doppler factor, then the (inner) radio axis may be closer to our line of sight than the large-scale morphology suggests, Indeed, a brightness ratio > 80 requires $\theta < 45°$ for any $\beta \leq 1$ in the formula above. In this case superluminal motion might be detected. A second experiment was performed in 1985 to look for motion of the 25-maa feature (Jones 1986). However, no significant change in the separation between the core and the 25-mas knot was found (v/c <0.3 h-l, where H_o = 100 h km S-l Mpc^{-1}).

Possible explanationa for the lack of detected transverse motion are: 1) the (inner) radio axis is aligned within just a few degrees of our line of sight, allowing small apparent transverse velocities even with large Lorentz factors, 2) the knot in the VLBI jet does not move with the bulk flow velocity of the jet, or 3) the two jets in this source are intrinsically asymmetric in radio brightness. The first possibility implies that the very straight VLA jet is well over a Mpc in length when deprojected, and the total extent of the source is several Mpc (larger than any other known source). The third possibility cannot be ruled out, but requires a mechanism other than Doppler boosting to make one jet brighter than the other from pc to 100+ kpc scales. We favor the second possibility y because other sources are known to contain both moving and stationary components (e.g., 3C395, 4C39.25). Thus, the observed motion of a jet feature does not always give an accurate indication of the bulk flow velocity.

2. OBSERVATIONS

We used a VLBI array composed of twelve telescopes in North America and

Europe to observe NGC 6251 at $\lambda = 18$ cm. The recorded bandwidth was 2 MHz, with left circular polarization. This experiment was carried out during 18 hours on 20 November, 1988, and resulted in a high dynamic range image of the initial 20 pc of the radio jet (figure 1).

The telescopes used for this experiment, along with their sensitivities at 18 cm, are listed in Table 1, All twelve telescopes used cooled receivers and hydrogen maser frequency standards, and all worked successfully. Due to the relatively low flux density (≈ 0.5 Jy) of the nuclear source for Mark-II VLBI, we did not attempt to use telescopes smaller than 25 m in diameter.

The data were correlated at the JPL/CIT Block II processor in Pasadena. The AIPS program CALIB (Schwab and Cotton 1983) was used to "fringe search" the resulting 2-second points, using a point source model. The amplitude correction applied by AIPS to fringes with non-zero residual delay errors was removed, as it is not appropriate for frequency-domain data from the Block II processor. The amplitude correction for non-zero residual fringe rate was left in. To avoid additional errors caused by truncation of the delay sine function near the edges of the correlator delay window, we were careful to keep fringes for all baselines within 400 ns of the window cent er. Tests by S. Meyers at Caltech have shown that for the Block II correlator in its normal 8-lag mode of operation, residual delays less than 400 ns cause amplitude errors of less than 4% and phase errors of less than 0,4 degrees. Data correlated with 8 lags and having delay residuals greater than 500 ns (2 lags) can suffer baaeline-dependent amplitude errors of 10% or more.

After fringe-fitting, the data were translated from AIPS to the Caltech VLBI package for editing, coherent time averaging, amplitude calibration, and hybrid map ping. The a *priori* calibration values obtained from telescope logs were updated by comparing amplitudes on baselines which nearly intersect in the u-v plane (the high declination of NGC 6251 prevents there being any true "crossing points").

The mapping process began with least-squares model fitting to the calibrated visibility data, A two-component Gaussian model was produced which was used for the first iteration (phase corrections only) of self-calibration. Additional iterations were made using time-independent amplitude corrections and then time-dependent amplitude corrections with a 30 minute time scale. The resulting CLEAN components were used to begin a new series of time-dependent self calibration, starting from the *a priori* calibrated data, After three iterations, the agreement factor (reduced χ^2) between the clean component amplitude and phases and the self-calibrated data was 1.97, and further improvement was very slow. Radial weighting was used during the Fourier transform step in each iteration. This exactly compensates for the decreasing density of u-v points with distance from the origin if the u-v tracks are circles. For NGC 6251, this is a good approximation.

The map produced by this procedure was quite good, with rms noise away from the peak approximately 300 μJy/beam; within a factor of two of the expected thermal noise level. However, the phase scatter on baselines to Haystack looked larger than implied by the SNR. This might be due to the Haystack radome, and as a test we removed all Haystack data and began the hybrid mapping process over again (using the current best map as our st arting model). After several iterations, a significantly improved map was produced. Its dynamic range (peak/rms) was somewhat better than our initial map, several spurious-looking weak features were removed, and the jet appeared more continuous. This map, with an off-source rms noise level of 230 μJy/beam, is shown in figure 2. Its agreement factor with the self-calibrated data is 1,93, No count erjet appeared in the map. The jet/counterjet brightness ratio close to the core (± 6 mas) is at least $\sim$100:1.

Figure 2 shows the maps from our 1983 and 1988 VLBI epochs plotted on the same scale and with the same contour levels, The second epoch map, shown in Jones (1986), is of poorer quality and has been used only for general consistency checks. Comparison of the two maps in Figure 2 shows that the peak surface brightness has increased from 155 mJy/beam in 1983 to 286 mJy/beam in 1988. This is consistent with VLA and Bonn total flux density measurements, which increased from 1.36 Jy to 1,50 at 18 cm.

3. THE LARGE-SCALE JET

We have used phased-array VLA data obt ained during our VLBI experiment to make a map of the kpc-scale jet with 3 arcsecond resolution. This is a factor of three increase in angular resolution compared to the phased-VLA map in Jones *et* *al.* (1986). Our new VLA map is shown in Figure 3, and the region where the jet begins to bend northward is shown in more detail in Figure 4. For the region between 50 and 140 kpc (using H_0 = 75 km $s^{-1}Mpc^{-1}$), this is the highest resolution map of this jet published to date. It shows multiple knots and variations in jet width and position angle. Throughout the region from 100 to 140 kpc, the jet is at least five times as wide as the synthesized beam. Note that the brightness gradient is steeper along the outer edge of the jet where it bends. There is a great deal of complex structure along the jet, as illustrated by the variations in surface brightness plotted in Figure 5. The jet is neither edge-brightened nor center-brightened; it has bright knots in apparently random places, and the ridgeline of the jet is curved in a non-simple fashion.

4. RESULTS

The maps shown in figure 2 show that the mas-scale jet in NGC 6251 has become brighter and less smooth during the five years from 1983 to 1988. This is illustrated in Figure 6, which shows surface brightness profiles along the jets from both epochs plotted on the same scale, The difference in position angle between the bright inner VLBI jet and the “25 mas knot” is similar in the 1983 and 1988 epochs (APA = 3,0° in 1983 and 2.5° in 1988), suggesting that the apparent variation seen in 1985 (APA = 6,0°) may be an artifact of the poorer quality of the 1985 map.

Another interesting aspect of figure 2 is the appearance of a brightness peak

≈ 12 mas from the core in the most recent map. This knot does not appear in the first or second epoch maps. Due to the higher quality of the first epoch map, we compare it with the third epoch map to derive a minimum transverse velocity for this new knot. Our (conservative) lower limit is 1.4 c, based on the assumpt ions that the knot has moved out from the core with constant velocity and that it has maintained a constant brightness (and thus must have been closer than 8 mas to the core in 1983), Using the second epoch map for comparison or assuming a decrease in brightness of the new knot with time would lead to a higher minimum transverse velocity.

The surface brightness of the VLBI jet decreases as $R^{-1.0}$ very near the core, and as $R^{-1.5}$ beyond about 6 maa, where R is the distance from the core. This latter slope is also consistent with the surface brightness in our VLA image out to at least 8 arcminutes. Figures 7 and 8 shows plots of jet surface brightness for both VLBI and VLA-scale jets. The -1,5 slope is somewhat steeper than the value found for the radio jets in the galaxy 3C120 (-1.27 $\pm$ 0.034; Walker, Benson, and Unwin 1987) but is consistent with the value for the quasar 3C345 (-1.45 $\pm$ 0.2; Unwin and Wehrle, 1992), The similar rates of decrease in radio jet brightness among these optically disparate objects suggests that the same physical mechanism is responsible for the conversion of jet kinetic energy into synchrotrons radio emission over a wide range of physical scales.

5. DISCUSSION

Can simple symmetric relativistic jet models explain the observed features of the NGC 6251 jet? The major difficulty is that the large jet/counterjet brightness ratio combined with the relatively low transverse velocities implies that the jet axis is within a few degrees of our line of sight, at least within several parsec of the nucleus. This in turn implies extremely large deprojected sizes for the large-scale radio structures associated with NGC 6251. One way out of this dilemma is to hypothesize that the radio jet bends so that its angle to our line of sight is small near the core and increases to some tens of degrees on the scale of the VLA jet. The very linear appearance of the kpc-scale jet makes this unlikely, since the bending would have to be precisely in a plane containing our line of sight to give the appearance of a straight jet.

Are we forced to invoke intrinsically asymmetric ejection from the nucleus (*e.g.,* Wang, Sulkanen, and Lovelace 1992)? No. Biretta, Owen, and Cornwell (1989) suggested that the radio jet in M87 might be intrinsically one-sided based on similar VLBI constraints, although they could not rule out relativistic flows with nearly stationary shocks. More recently, the idea of an intrinsically one-sided jet in M87 has been ruled out by the detection of an optical hot spot in the counterjet direction (Sparks *et al.*, 1992; Stiavelli *et al.*, 1992). In the case of NGC 6251 the best evidence for symmetric jets is the VLA-scale counterjet. Our failure to detect a pc-scale counterjet (at a brightness ratio considerably greater than the kpc-scale jet and counterjet display near the nucleus) is difficult to reconcile with simple twin-jet models, but only if the jets are not moving relativistically. We propose that the jets in NGC 6251 are relativistic, and that the nearly stationary "25-mas knot" is caused by a nearly stationary shock within the jet (similar to those illustrated in figure 4 of Daly and Marscher [1988]).

6. SUMMARY

We have presented a third epoch 18-cm VLBI image of the radio jet in the giant radio galaxy NGC 6251, It shows a minor brightness peak at nearly the same distance from the core as the "25-mas knot" seen in the first and second epoch images. This feature is much less pronounced in the third epoch, and a relatively bright, new knot has appeared ~ 12 mas from the core. If this new component had a constant brightness during the five years separating the first and third observing epochs, then it must have moved away from the core with an apparent speed of at least 1.4 c (compared with an upper limit of 0,23 c from motion of the 25-mas knot). This suggests that jet models with stationary shocks may be applicable to NGC 6251. However, we cannot yet rule out a local brightening of the inner jet in favor of a new moving component. The surface brightness of the jet in NG C 6251 decreases with distance from the core at a rate similar to that found in known superluminal objects.

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TABLE 1

Parameters of Telescopes Used in 1988 VLBI Experiment

Telescope	Diameter (meters)	Sensitivity (K/Jy)	System Temp. (K)
Onsala	26	0.093	42
Effelsberg	100	1.00*	40
Westerbork	3x25	0.27	57
Medicina	32	0.10*	75
Jodrell Bank	76	1.00	47
Madrid	64	0.65	39
Haystack	37	0.085	90
Green Bank	43	0.296	23
Fort Davis	25	0.09	70
Very Large Array	27x25	2.314	68
Pie Town	25	0.10	38
Owens Valley	40	0.21	54

* (lower than usual value for this telescope)

FIGURE CAPTIONS

FIGURE 1. The 1988 18-cm VLBI image of NGC 6251, The contours levels are -0.05, 0.05, 0,1, 0.2, 0,5, 1, 2, 5, 10, 20, and 50% of the peak, which is 274 mJy/beam. The convolving beam is a circular Gaussian with FWHM = 3.0 maa, and the position angle of the jet has been rotated by 30° clockwise, The tick marks along the axes are 6.5 mas apart.

FIGURE 2. The 1983 (Top) and 1988 (Bottom) VLBI images of NGC 6251 at λ = 18 cm. In this figure both images are plotted with surface brightness contours of -0.25, 0.25, 0.5, 1, 2, 5, 10, 15, 25, 35, 50, 70, and 90% *of* 268 mJy/beam. The angular scale is 4,5 mas per tick mark,

FIGURE 3. The phased-array VLA image of the NGC 6251 jet, made from data obtained during our 1988 VLBI observations. The jet is shown out to approximately 4.5 arcminutes from the core (at left end of jet). The clean beam diameter was 3.0 arcseconds (FWHM). The position angle of the jet has been rotated 25 degrees clockwise, Contours are plotted at -0.15, 0.15, 0.2, 0.3, 0.5, 0.7, 1.0, 1.5, 2.0, 2.5, 3.5, 5.0, 10, and 50% of the peak brightness, which is 1.55 Jy/beam.

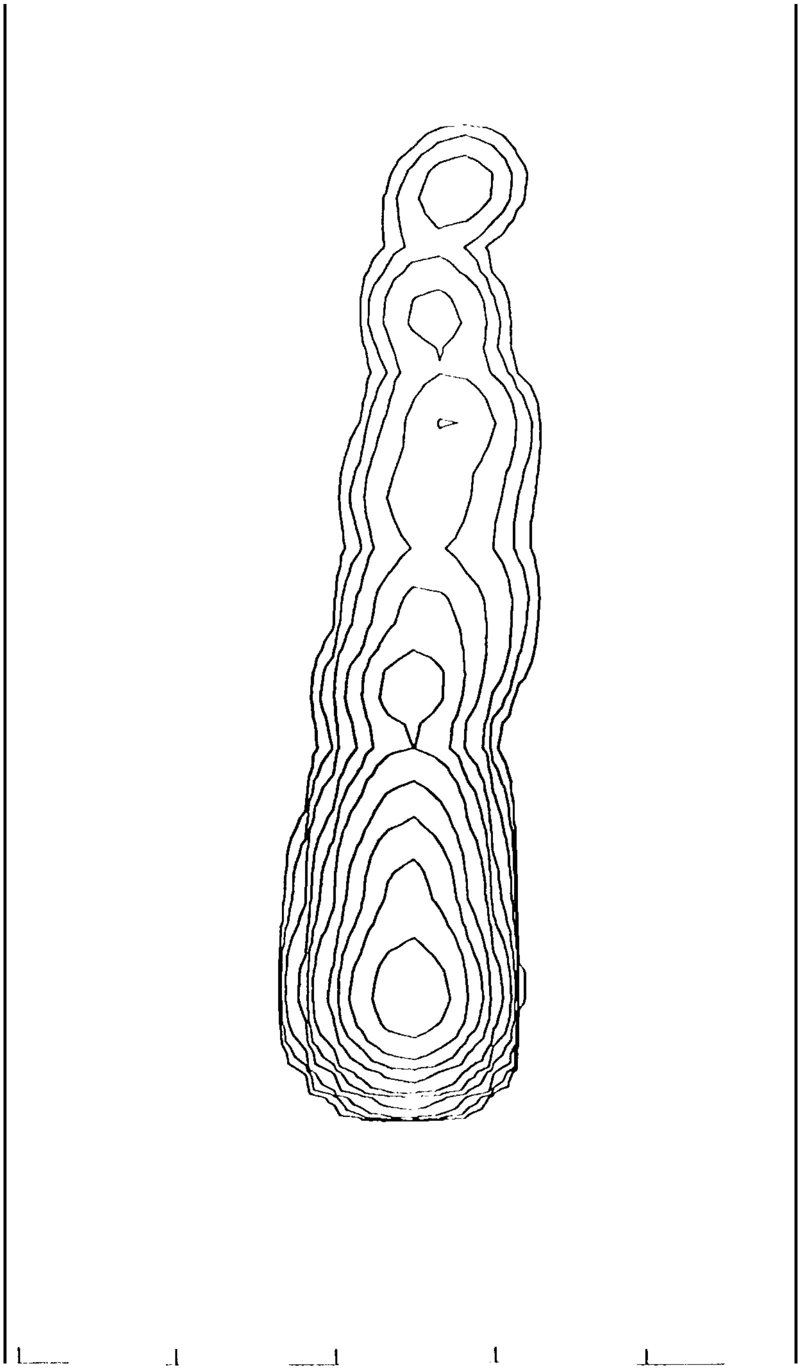
FIGURE 4. Expanded view of the region in Figure 3 between 170 and 275 arcseconds from the core, The contours are -0,1, 0.1, 0,2, 0.3, 0,5, 0.7, 1,0, 1.3, 1,6, and 2.0% of the peak (1,55 Jy/beam).

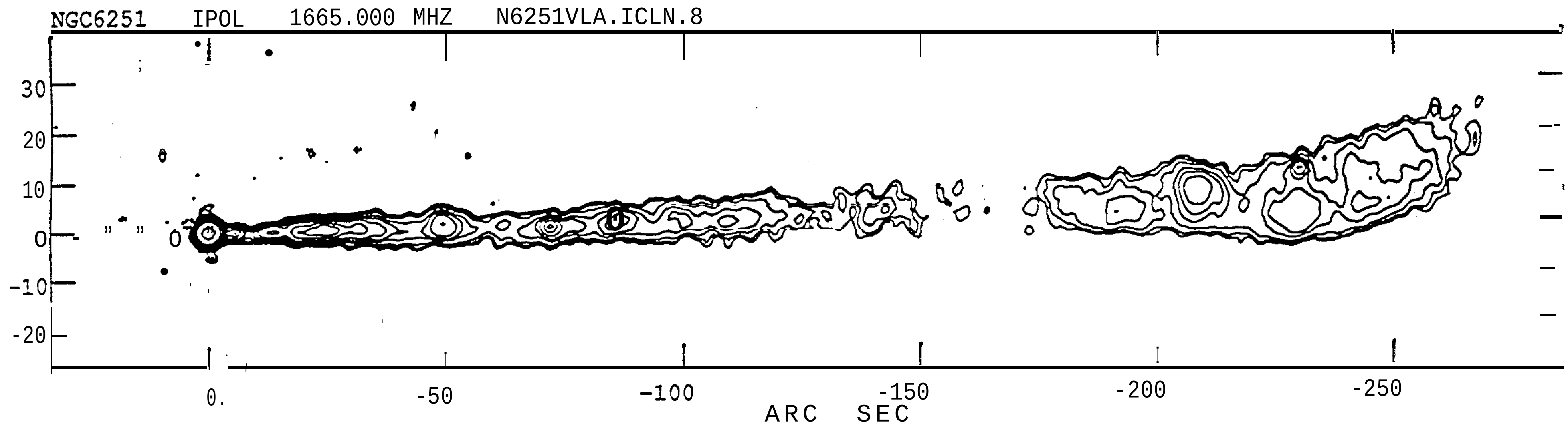
FIGURE 5. Surface brightness profile along the NGC 6251 jet, The core (corresponding to the nucleus of the galaxy) is at the left edge of the plot, and has a peak value of approximately 1300 mJy/beam.

FIGURE 6. Surface brightness along the VLBI jet in 1983 (top) and 1988 (bottom), In both cases the vertical scale goes from -1 to 10 mJy/beam, and the zero point of the horizontal scale is arbitrary.

FIGURE 7. Surface brightness of the NGC 6251 jet as a function of distance from the core, The points to the left of the large gap are from our 18-cm VLBI maps, and the points to the right of the gap are from 18-cm VLA maps. All points have been normalized to a circular beam size of 3.0 mas. The straight line has a slope of -1.54.

FIGURE 8. Surface brightness of the NGC 6251 jet within 15 mas of the core. Note the steepening of the surface brightness gradient near 5 mas (log(5) = 0.7).

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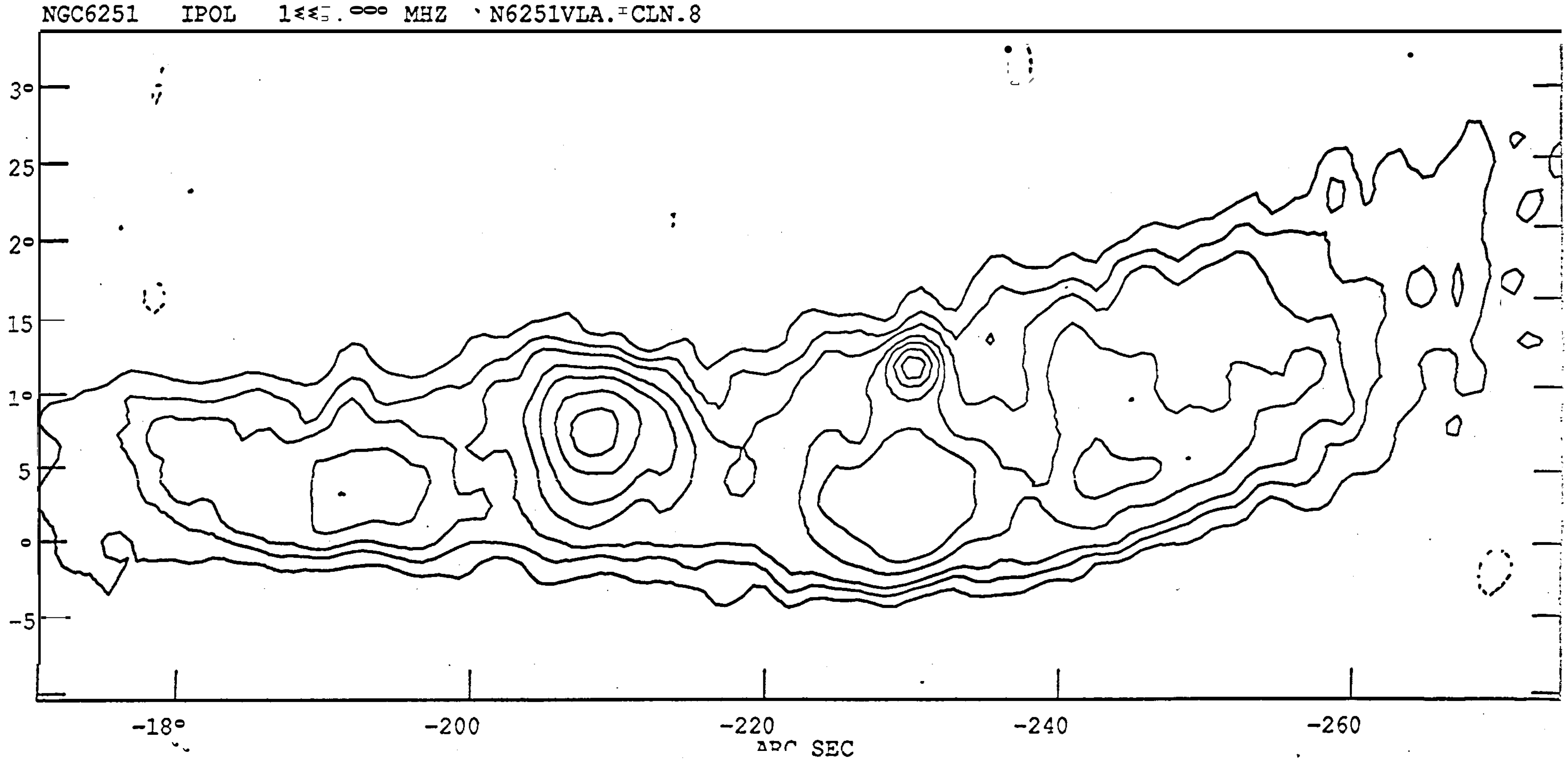
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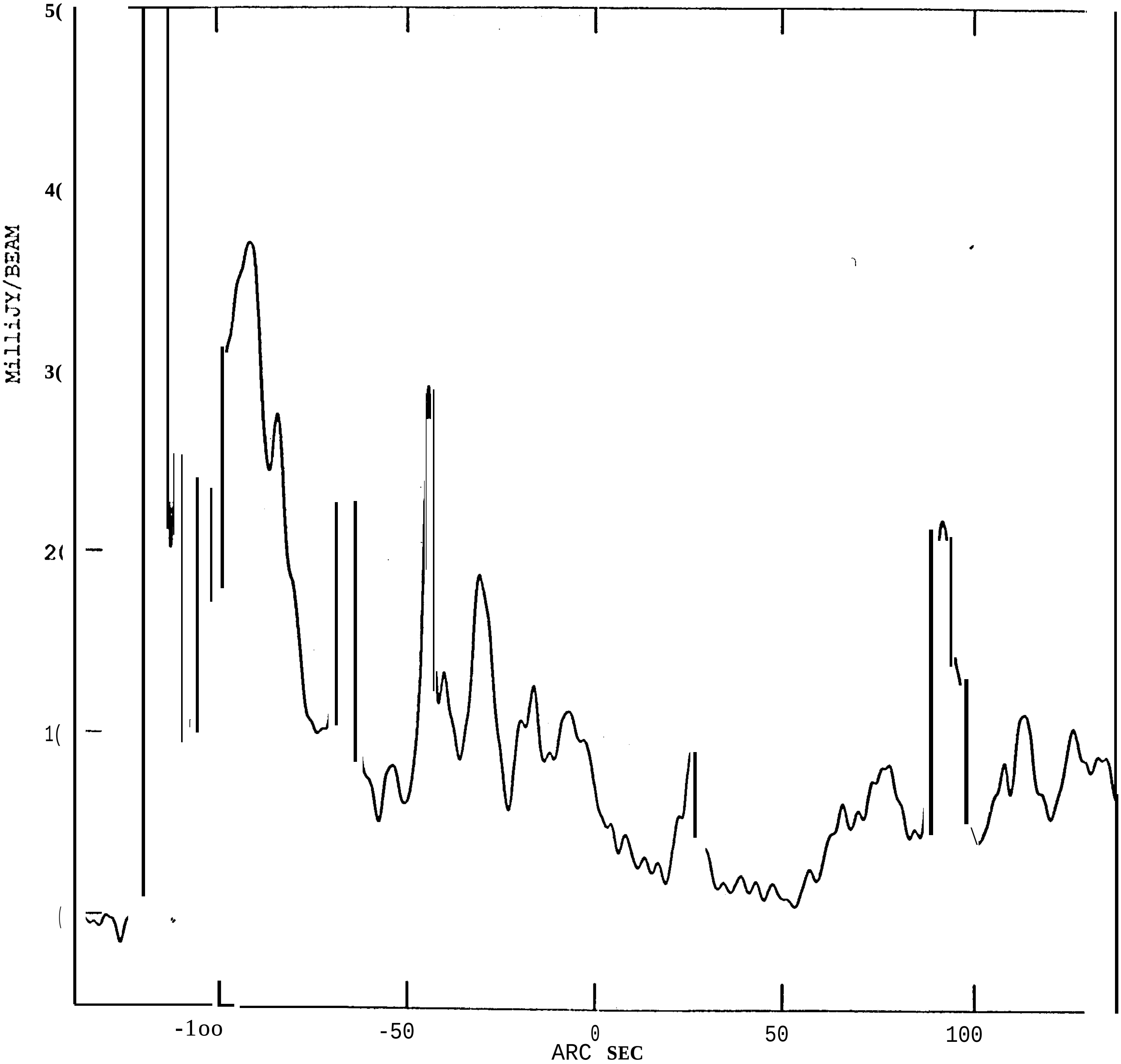

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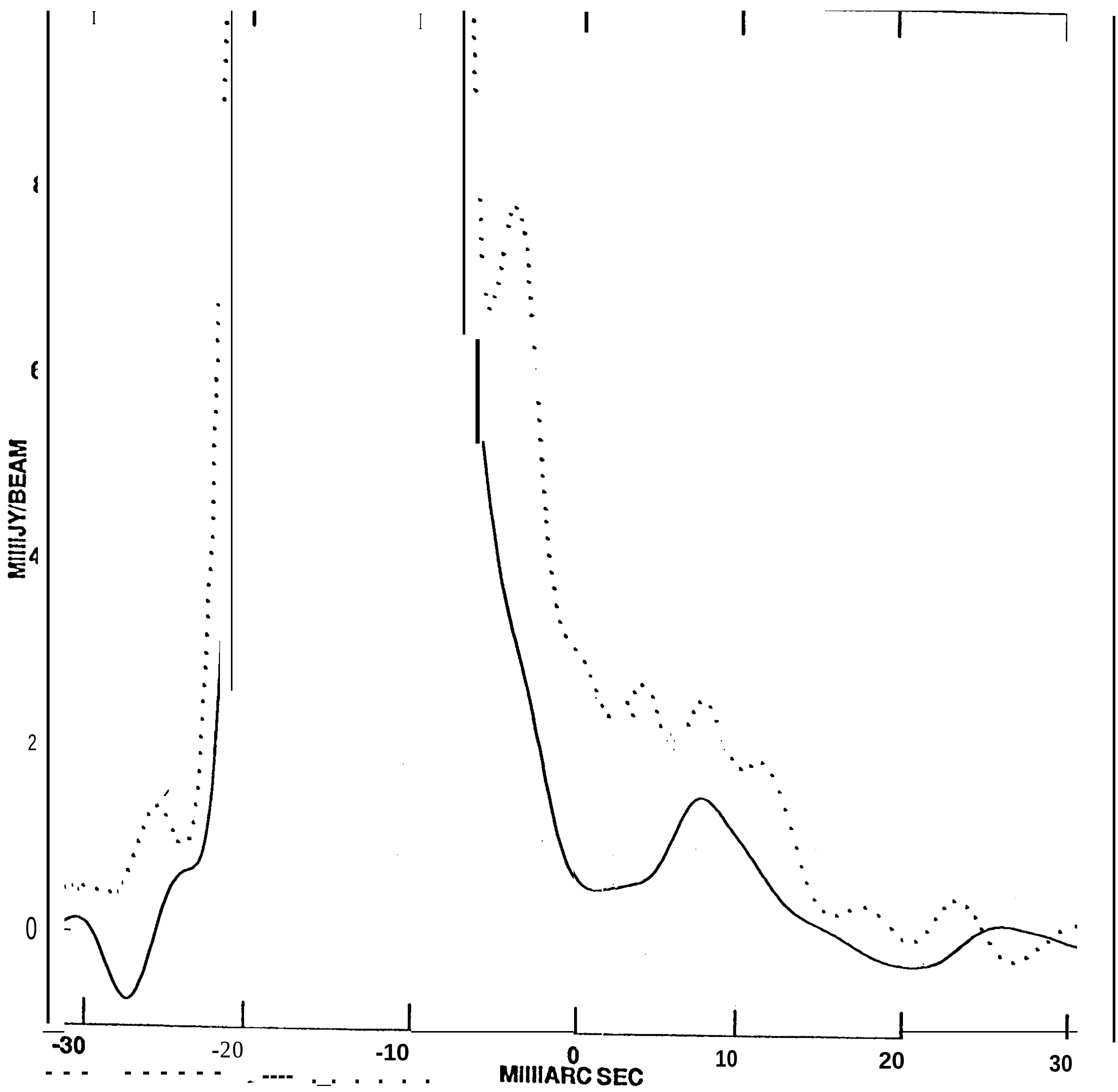

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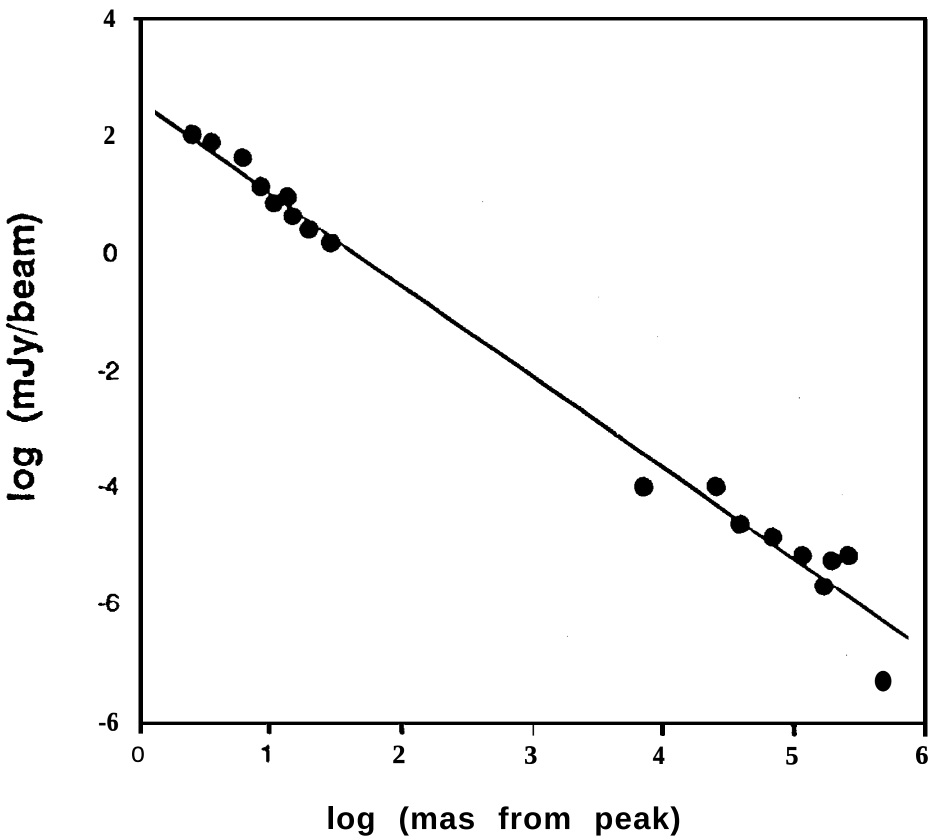
SURFACE BRIGHTNESS OF NGC 6251 JET



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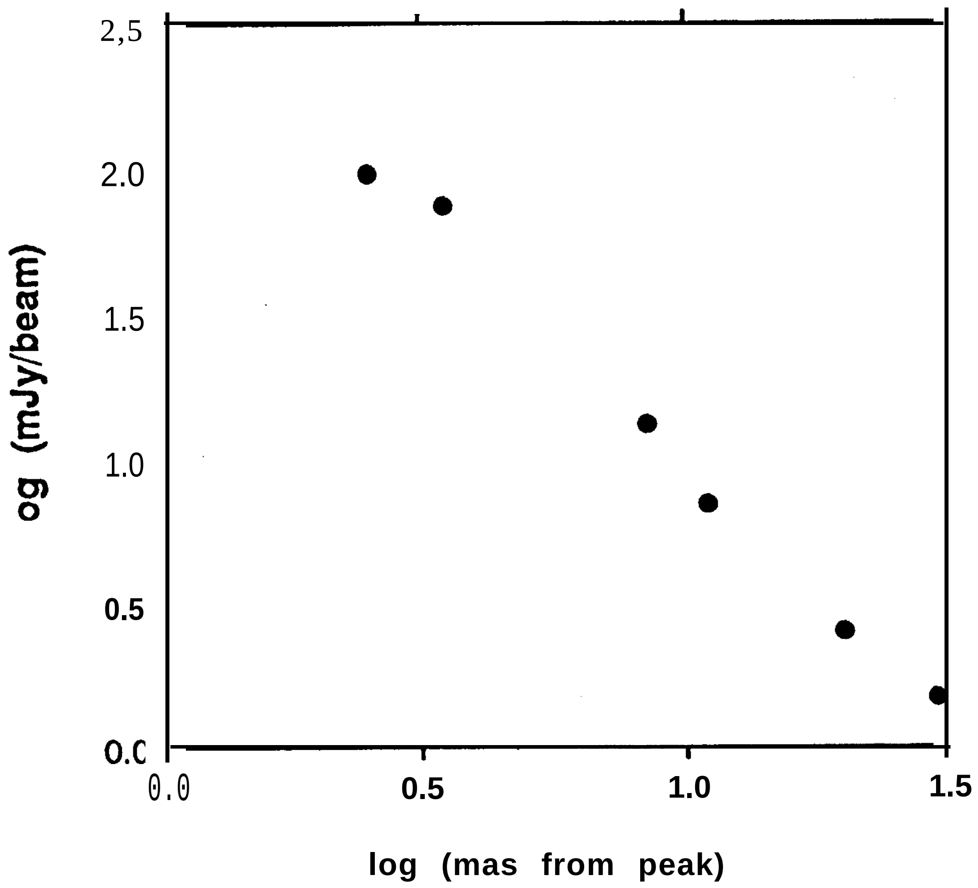

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